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Review

A Review of Factors Affecting the Acute Exercise-Cognition Relationship in Children and Adolescents

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Abstract

It is well documented that an acute bout of exercise has a positive effect on subsequent cognitive function in children and adolescents. However, the effect of: the exercise characteristics (i.e. intensity, duration and modality), the cognitive domain assessed, and moderating variables (such as the participant's age, physical fitness and baseline cognitive abilities); all of which affect this relationship are poorly understood. Therefore, the purpose of this review is to examine the impact of these variables on the acute exercise-cognition relationship in children (aged 6-11 years) and adolescents (aged 12-18 years). Searching the published literature from 2008 to date yielded 22 relevant studies in children and 14 relevant studies in adolescents. This review examines the effects of exercise characteristics (section 2), the cognitive domain assessed (section 3), and the time course of the effects (section 4), alongside the moderating effects of participant characteristics (section 5). The findings indicate that moderate intensity of ~ 30 min duration has positive effects across cognitive domains in children, whilst moderate-high intensity exercise of 10-30 min duration appears most beneficial in adolescents. Findings also suggest that the beneficial effects last for ~ 45 min post-exercise and, tentatively, may be more pronounced in children and adolescents with higher physical fitness levels. Future research in this area should continue to explore the factors (e.g. exercise characteristics, cognitive domains assessed and moderating variables) affecting the acute exercise-cognition relationship in children and adolescents. Where possible these factors should be controlled (or at the very least measured and reported), to allow a more complete interpretation of the findings and extending our understanding of this complicated relationship.

Keywords
Exercise; cognitive function; exercise intensity; exercise duration; exercise modality; working memory; attention; perception; executive function

1. Introduction

There has been great interest in recent years regarding the effects of an acute bout of exercise on cognitive function. Cognitive function can be defined as "a variety of brain-mediated functions and processes, that allow us to perceive, evaluate, store, manipulate and use information from external (e.g. environment) and internal (e.g. experiences, memory) sources and then respond to this information" [1]. Cognitive function can be split into six main domains: memory, attention, perception, executive function, language and psychomotor functions [1]. Given this definition, it is clear that cognitive function will have implications for the ability of children and adolescents in terms of learning and subsequently academic achievement at school; as such it is unsurprising that this population has been a focus for literature in this area.

A number of reviews and meta-analyses have concluded that an acute bout of exercise leads to a small, but positive, effect on subsequent cognitive performance in children and adolescents [2-4]. However, the acute exercise-cognition relationship is not a simple phenomenon. There are a number of moderating factors (e.g. age, physical fitness), as well as characteristics of the exercise (e.g. intensity) and the cognitive domain being assessed; which will impact upon this relationship. To be clear, a moderator is any factor that affects the strength of a relationship between the independent (exercise) and dependent (cognitive function) variables [5]. In this instance, moderating variables include the participant characteristics, such as; age, baseline physical activity levels, physical fitness, baseline cognitive ability and weight status; as well as the time course between exercise and cognitive assessment. Characteristics of the independent variable (exercise) also need to be considered and include; intensity, duration and modality. Finally, the varying domains of the dependent variable (cognition) need consideration with regard to this relationship. An overview of this relationship is shown in Figure 1.

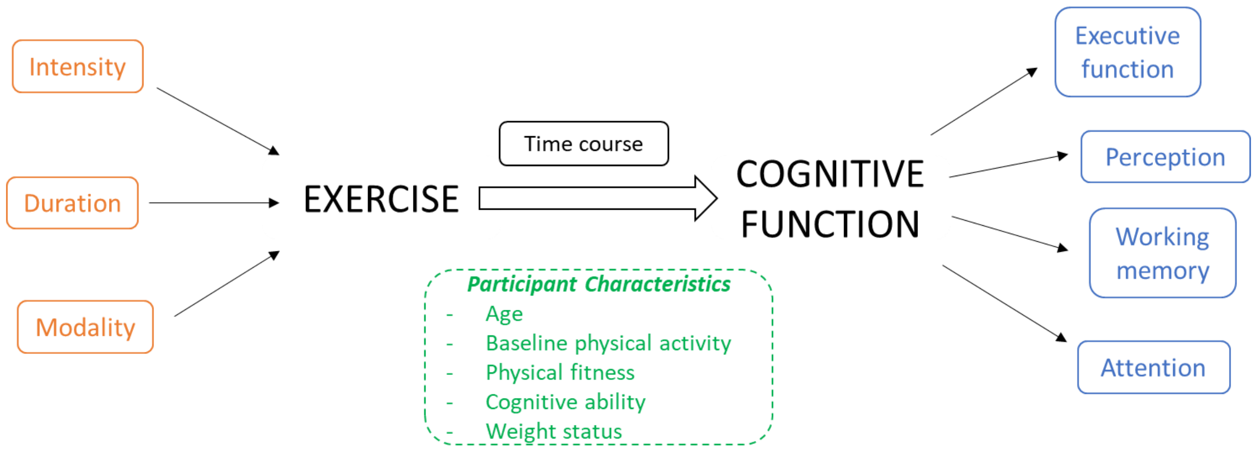

Figure 1 An overview of the exercise-cognition relationship. Exercise characteristics are shown in orange, cognitive domains in blue and potential moderating variables in green.

In the literature to date there has been a lack of focus on the effect of key moderators, the exercise characteristics and the cognitive domains assessed, in the acute exercise-cognition relationship in children and adolescents. The purpose of this review is to take each of these moderators and characteristics in turn and to summarise the evidence regarding their effect on this important relationship.

Age has been suggested as a key moderating variable in the acute exercise-cognition relationship in children and adolescents, such as in previous meta-analyses [2, 4]. Interestingly, Sibley & Etnier [4] suggested the post-exercise cognitive effect was greater in young adolescents and children than in older adolescents, whereas Chang et al. [2] found the effects to be greater in adolescents compared to younger children. This discrepancy in results could be attributed to the different methods used to categorise participants by age, with Sibley & Etnier [4] using four categories (4-7, 8-10, 11-13 and 14-18 yrs) as opposed to just two (6-13 and 14-17 yrs) used by Chang et al. [2]. Another explanation might be due to the number of participants available for the effect size calculations, with Sibley & Etnier [4] having fewer participants for their younger populations compared to Chang et al. [2]. Furthermore, Sibley & Etnier [4] included unpublished studies within their analyses, which typically had larger effect sizes compared to published work. Despite this ambiguity, it is clear that age is an important moderating factor in the acute exercise-cognition relationship and thus, this review will discuss the effects in children (aged 6-11) and adolescents (aged 12-18) separately. An overview of the available studies in children is provided in Table 1 and in adolescents in Table 2.

Table 1 An overview of the studies examining the acute effects of exercise on cognitive function in children.

Study	*Participant Characteristics*	*Exercise Characteristics*	*Cognitive Tests (Domains)*	*Timing*	*Results*
Altenburg, Chinapaw, & Singh [6]	n = 56 10 – 13 yrs	*D*: 20 min *I:* MOD *M*: 1 x AE vs. 2 x AE vs. sedentary classroom activity	Sky Search- Test of Selective Attention in Children *(Attention)*	Pre, immediately-, 20 min- and 110 min post condition	↑ selective attention across the morning following two 20 min bouts of aerobic exercise
Chen et al. [7]	n = 98 8 – 11 yrs	*D*: 30 min *I:* MOD *M*: Running vs. seated reading	Modified EFT (*Executive Function*) The More-odd Task (*Executive Function*) Modified Visual 2-back Task (*Working Memory*)	Pre and post	↑ response times 25 min post exercise ↑ shifting response times 25 min post exercise ↑ response times 25 min post exercise
Drollette et al. [8]	n = 40 8 – 10 yrs High performer Low Performer	*D:* 20 min *I:* MOD *M:* Treadmill walking vs. seated rest	EFT *(Executive Function)*	Post	↑ accuracy and reduced accuracy interference in low performers post exercise No effects seen in high performing group
Drollette et al. [9]	n = 36 9 – 11 yrs 9.9 ± 0.7 yrs	*D:* ~ 20 min *I:* MOD *M:* Treadmill walking vs. resting control	Modified EFT *(Executive Function)* Modified Spatial n-Back Task (*Working Memory*)	Pre and post	Exercise facilitated maintenance of response accuracy over time, compared to rest No effects

Egger, Conzelmann, & Schmidt [10]	n = 216 7 – 9 yrs 7.9 ± 0.4 yrs	*D*: 20 min *I:* High PE = 67% HR max, Low PE = 47% *M:* Classroom-based High PE, High CE vs. High PE, Low CE vs. Low PE, High CE vs. Low PE, Low CE (control)	Backward Colour Recall Task (*Working Memory*) Modified EFT *(Executive Function)*	Pre and post	No overall effect of physical exertion (PE) High cognitive engagement (CE) reduced shifting performance, compared to low cognitive engagement
Ellemberg & St-Louis-Deschênes [11]	n = 36 7 yrs boys n = 36 10 yrs boys	*D:* 30 min *I:* MOD *M:* Cycling vs. resting control	Simple Reaction Time Task *(Perception)* Choice Response Time Task *(Perception)*	Pre and post	↑ reaction time post exercise in both age groups ↑ choice response time post exercise in both age groups
Gallotta et al. [12]	n = 116 8 – 11 yrs	*D*: 50 min *I:* MOD - VIG *M:* CE-PE vs. AE vs. normal school lesson (CE)	d2 *(Attention)*	Pre, immediately- & 50 min- post	↑ attentional performance following all three conditions Improvements lasted 50 min CE-PE resulted in the smallest improvement
Gallotta et al. [13]	n = 138 8 – 11 yrs	D: 50 min *I:* MOD – VIG *M:* CE-PE vs. AE vs. normal school lesson (CE)	d2 *(Attention)*	Pre and post	↑ attentional performance following all three conditions CE-PE resulted in smallest improvement

Hillman et al. [14]	n = 20 9 – 10 yrs	*D*: 20 min *I:* MOD 60% HR max *M:* Walking vs. resting control	Modified EFT *(Executive Function)*	Post	↑ response accuracy post exercise, no effects on reaction time
Howie, Schatz, & Pate [15]	n = 96 9 – 12 yrs 10.7 ± 0.6 yrs	D: 5, 10, 20 min I: MOD – VIG M: Classroom-based AE vs. 10 min rest (sedentary classroom activity)	Trail-Making Test *(Attention and Executive Function)* Digit Recall *(Working Memory*	Pre and post	No effect of exercise No effect of exercise
Ishihara et al. [16]	n = 74 6 – 12 yrs High performer Low performer	*D*: 50 min *I:* Not stated *M*: Technique-based tennis (high CE) vs. game-based tennis (low CE) vs. resting control	Stroop Test *(Executive Function)* 2-Back Task *(Working Memory)* Local-Global Task *(Executive Function)*	Pre, 15 min post	No effect of exercise ↑ working memory post high CE and low CE exercise, no difference between groups ↑ reaction time post high CE and low CE exercise, greatest improvement post high CE exercise Greatest improvements in low performers
Ishihara et al.[17]	n = 40 6 – 12 yrs 9.6 ± 1.7 yrs	*D*: Not stated *I*: 68% HR max *M:* Tennis, coordination training (high CE) vs. games (high CE) vs. rallying (low CE) vs. non-PA (control)	Stroop Test *(Executive Function)* 2-Back Task *(Working Memory)*	Pre and post	↑ inhibition post games-based (high CE) exercise ↑ working memory post coordinative (high CE) exercise

Jager et al. [18]	n = 104 6 – 8 yrs 7.9 ± 0.4 yrs	*D:* 20 min *I:* MOD - VIG 156.76 ± 14.09 beats·min^{-1} *M:* CE vs. resting control	N-back Task *(Working Memory)* Modified EFT *(Executive Function)*	Pre, immediately-, 20min- and 40 min- post	No effect of exercise ↑ inhibition immediately- and 20 min- but not 40 min- post CE
Jager et al. [19]	n = 217 10 – 12 yrs 11.4 ± 0.5 yrs High performer Low performer High fit Low fit	*D:* 20 min *I:* 50%-80% HR max *M:* CE-PE vs. PE vs. CE vs. resting control	Non-Spatial N-Back Task *(Working Memory)* EFT *(Executive Function)*	Pre and post	No effect of exercise ↑ inhibition post PE, compared to CE-PE, CE and rest, but only in children with higher fitness and/or academic achievement
Janssen et al. [20]	n = 123 10 – 11 yrs 10.4 ± 0.6 yrs	*D*: 15 min *I:* MOD vs. VIG *M*: MOD-PE (jogging, passing, dribbling) vs. VIG-PE (running, jumping, skipping) vs. CE vs. resting control	Sky Search *(Attention)*	Pre and post	↑ selective attention post rest, MOD-PE and VIG-PE Largest improvement post MOD-PE No significant difference between VIG-PE and rest
Lambrick et al. [21]	n = 20 8 – 10 yrs 8.8 ± 0.8 yrs	*D:* 15 min *I:* MOD *M:* CONT vs. INT treadmill running	Stroop Interference Task *(Executive Function)*	Pre, 1 min-, 15 min- and 30 min- post	↑ completion time and reaction time post INT compared to CONT exercise Improvements observed from 1 min- and maintained for 30 min- post exercise
Niemann et al.[22]	n = 42 9 – 10 yrs 9.7 ± 0.4 yrs	*D*: 12 min *I:* HI (85%-90% HR max) *M:* Running vs. resting control	d2 *(Attention)*	Pre and post	↑ sustained and selective attention post exercise compared to rest

Pesce et al. [23]	n = 60 11 – 12 yrs	*D*: 60 min *I:* Not stated *M*: Team games (high CE) vs. circuit training (low CE) vs. resting control	Free-Recall Memory Task *(Working Memory)*	Immediately- and approx. 30 min- post	↑ memory performance post exercise compared to rest Only team games (high CE) significantly enhanced both immediate and delayed memory performance
Pontifex et al.[3]	n = 20 9 – 10 yrs 9.8 ± 0.1 yrs	*D*: 20 min *I*: MOD 65%-75% HR max *M:* Treadmill running vs. seated reading (control)	Modified EFT *(Executive Function)*	Post	↑ response accuracy post exercise
Schmidt et al. [24]	n = 90 11 ± 0.6 yrs	*D:* 45 min *I:* Self-selected *M:* Classroom-based CE-PE vs. resting control	d2 *(Attention)*	Pre, immediately- and 90 min- post	↑ attention performance 90 min post CE-PE
Stein et al. [25]	n = 102 5 – 6 yrs 6 ± 0.5 yrs	*D:* 20 min *I:* 65%-70% HR max *M:* CE-PE vs. resting control	Simon Says *(Executive Function)* Hearts and Flowers Task *(Executive Function)*	Pre (1 week prior) and post	No effect of CE No effect of CE
Vazou & Smiley-Oyen [26]	n = 35 9 – 11 yrs 10.5 ± 0.7 yrs Overweight Normal weight	*D*: 10 min *I:* 64%-76% HR max *M:* Classroom-based CE-PE vs. CE	EFT *(Executive Function)*	Pre and post	↑ reaction time post CE-PE Greatest improvements in overweight children, compared to normal weight children

↑ Positive effect; ↓ Negative effect; AE Aerobic Exercise; CE Cognitively Engaging; CE-PE Cognitively Engaging Physical Exercise; CONT Continuous Exercise; D Duration; EFT Eriksen Flanker Test; HI High-Intensity; HRmax Maximum Heart Rate; I Intensity; INT Intermittent Exercise; M Modality; MOD Moderate Intensity; PA Physical Activity; PE Physically Engaging; RE Resistance Exercise; TTE; Time To Exhaustion; VIG Vigorous Intensity.

Table 2 An overview of the studies examining the acute effects of exercise on cognitive function in adolescents.

Study	*Participant Characteristics*	*Exercise Characteristics*	*Cognitive Tests (Domains)*	*Timing*	*Results*
Berse et al. [27]	n = 227 13 – 17 yrs 14.8 ± 0.9 yrs	*D:* TTE *I:* +25W every 10 s, 70 rpm *M:* Cycling vs resting control	Modified switching task *(Executive Function)*	Post-condition	↑ shifting post-exercise (reduced switch costs)
Browne et al. [28]	n = 20 10 – 16 yrs 13 ± 1.8 yrs	*D:* 20 min *I:* 65% – 75% HRR *M:* Running vs resting control	Stroop Test *(Executive Function)*	Pre and 10 min post	↑ response time 10 min post-exercise (incongruent level)
Budde et al. [29]	n = 99 13 – 16 yrs 14.9 ± 0.8 yrs	*D:* 10 min *I:* MOD 122 beats·min^{-1} *M:* CE vs normal sports lesson	d2 *(Attention)*	Pre- and post	↑ attention and concentration in both groups Greater ↑ in the CE group.
Budde et al. [30]	n = 59 15 – 16 yrs 14.4 ± 0.5 yrs High Performer Low Performer	*D:* 12 min *I:* 50% – 65%, 70% – 85% HRmax *M:* Running vs resting control	Letter Digit Span *(Working Memory)*	Pre and post	↑ performance for 50% – 65% HRmax Greater ↑ for those with lower Letter Digit Span scores pre-exercise.
Cooper et al.[31]	n = 45 12 - 13 yrs 13.3 ± 0.3 yrs	*D:* 10 min *I:* HI (Sprints) 172 beats·min^{-1} *M:* Shuttle running vs resting control	Visual Search *(Attention)* Stroop Test *(Executive Function)* Sternberg Paradigm *(Working Memory)*	Pre and 45 min post	↑ response times post-exercise ↓ Accuracy post-exercise No effect of exercise ↑ response times post-exercise ↓ response times post-control

Cooper et al. [32]	n = 44 12.6 ± 0.6 yrs	*D:* 10 min 10 x 10 s *I:* HI (Sprints) 181 beats·min^{-1} *M:* Running vs resting control	Stroop Test *(Executive Function)* Digit Symbol Substitution *(Working Memory)* Corsi Blocks *(Working Memory)*	Pre-, immediately- and 45 min-post	↑ response times 45 min post-exercise (Congruent) ↑ response times immediately post-exercise (Incongruent) No effect of exercise No effect of exercise
Cooper et al. [33]	n = 39 11 - 13 yrs 12.3 ± 0.3 yrs High Fit Low fit	*D:* 60 min *I:* MOD – HI 158 ± 11 beats·min^{-1} *M:* Games-based (Basketball) vs resting control	Stroop Test *(Executive Function)* Sternberg Paradigm *(Working Memory)* Digit Symbol Substitution *(Working Memory)* d2 *(Attention)*	Pre-, immediately- and 45 min post-	↑ response times immediately- and 45 min-post - exercise (Incongruent) ↑ response times for 5-item level immediately post-exercise No effect of exercise No effect of exercise ↑ greater in high fit
Etnier et al. [34]	n = 43 11 – 12 yrs	*D:* TTE *I:* Incremental +0.5km·h^{-1} *M:* Running (MSFT) vs normal sports lesson	Rey Auditory Verbal Learning Test *(Memory)*	Post- condition 24 hr recall test performed.	↑ learning and recall in the exercise group No effect on 24 hr recall ability.
Harveson et al.[35]	n = 94 15 - 16 yrs 16.1 ± 0.8 yrs	*D:* 30 min *I:* 50% – 60% HRmax *M:* AE (walking/jogging), RE and resting control	Stroop test *(Executive Function)* Trail-making test *(Attention)*	Approx. 5 – 40 min post	↑ response times for AE and RE compared to control ↑ part B for AE compared to RE and control
Hogan et al. [36]	n = 30 14.2 ± 0.5 yrs High Fit Low fit	*D:* 20 min *I:* 60% HRmax *M:* Cycling vs resting control	Modified EFT *(Executive Function)*	Post-condition	↑ response times for High fit participants post-exercise compared to control Unfit had higher error rates during rest trial.

Schmidt, Benzing & Kamer [37]	n = 102 11.7 ± 0.4 yrs	*D:* 10 min *I:* MOD *M:* CE-PE, CE, PE and resting control.	d2 *(Attention)*	Pre- and 10 min post-	↑ focused attention and enhanced processing speed for CE group PE had no effect on cognitive performance.
Soga, Shishido, & Nagatomi [38][a]	n = 28 15 -16 yrs 15.6 ± 0.5 yrs	*D:* 13 min *I:* 60% HRmax *M:* Treadmill walking vs resting control	EFT *(Attention)* Spatial n-back *(Working Memory)*	Pre-, during and immediately post.	↓ accuracy during walking vs post-walking No effect of exercise on response times ↓ response times during exercise vs during rest.
Soga, Shishido, & Nagatomi [38][a]	n = 27 15 -16 yrs 15.8 ± 0.4 yrs	*D:* 13 min *I:* 70% HRmax *M:* Treadmill walking vs resting control	EFT *(Attention)* Spatial n-back *(Working Memory)*	Pre-, during and immediately post.	No effect of exercise ↓ accuracy during exercise vs control ↓ response times during exercise vs control
Stroth et al. [39]	n = 33 14.2 ± 0.5 yrs High Fit Low fit	*D:* 20 min *I:* 60% HRmax *M:* Cycling vs resting control	Modified EFT *(Executive Function)*	Post-condition	No effect of exercise
van den Berg et al. [40]	n = 195 10 – 13 yrs 11.7 ± 0.7 yrs	*D:* 10 min *I:* MOD *M:* AE, RE, CE and resting control.	d2 *(Attention)* Letter Digit Substitution Test *(Working Memory)*	Pre- and post-condition	No effect of exercise compared to control No effect of exercise compared to control No effects of exercise type

[a] Two experiments from the same paper.

↑ Positive effect; ↓ Negative effect; AE Aerobic Exercise; CE Cognitively Engaging; CE-PE Cognitively Engaging Physical Exercise; CONT Continuous Exercise; D Duration; EFT Eriksen Flanker Test; HI High-Intensity; HRmax Maximum Heart Rate; I Intensity; INT Intermittent Exercise; M Modality; MOD Moderate Intensity; PA Physical Activity; PE Physically Engaging; RE Resistance Exercise; TTE; Time To Exhaustion; VIG Vigorous Intensity.

This review provides an overview of the research in each of these areas over the past decade. Where possible, conclusions will be made regarding the effect of the moderating variables, exercise and cognitive characteristics, identified in Figure 1, on the acute exercise-cognition relationship in children and adolescents, and important avenues for future research within this area will be highlighted.

2. Method

To obtain all relevant literature, searches were carried out on Pub Med, Sport Discus and Scopus. Search terms included exercise-related terms, such as “exercise”, “physical activity”, “physical exercise”; and cognitive-related terms such as “cognitive function”, “cognition”, “cognitive performance” and “brain function”; using the logical operator “and”. Additional fields to specify the target population, using “children”, “adolescents”, “young people”, and the bout type, “acute”, were also included. On top of this, the reference lists of appropriately identified papers were reviewed for appropriate literature. Eligibility of studies for inclusion was based on the following criteria: 1) Participants consisted of children (6-11 years) or adolescents (12-18 years) only; 2) Participants did not present any health related issues that would interfere with cognitive function; 3) The study focused on a single bout of exercise; 4) The study assessed cognitive function using at least one of the established domains (i.e. attention, executive function, working memory); 5) The inclusion of a comparison group/trial; 6) The article was available as full text and written in English. Searching the published literature from 2008 to date yielded 22 relevant studies in children and 14 relevant studies in adolescents.

3. Exercise Characteristics

A clear influence on the acute exercise-cognition relationship are the characteristics of the exercise undertaken. The characteristics of exercise, including the intensity, duration and modality, must therefore be considered when examining the effect on cognition. Undoubtedly, these characteristics are linked; for example, exercise which is very high intensity will subsequently be of a shorter duration. Therefore, in this review, the effects of these exercise characteristics are considered together. Moreover, conclusions will be drawn with regards to how the intensity, duration and modality of exercise can be manipulated to elicit maximal cognitive benefits in children and adolescents.

3.1 Children

The majority of research in children (see Table 1), has focused on the effects of walking and running and evidence suggests that such exercise provides significant benefits across a range of domains of cognition including attention [6, 22], working memory [7] and executive function [7-9, 14, 21, 41]. It must be noted, however, that some research has failed to find effects of walking or running on these same domains (working memory: [9, 15]; attention and executive function: [15]), although this may be due to a shorter exercise duration (<20 min) being used.

Many authors agree that the duration of exercise is a significant factor influencing the effect that acute exercise has on subsequent cognition [2-4]. In their meta-analysis, Chang et al. [2] concluded that exercise of shorter durations leads to negligible effects on cognitive performance, while exercise of longer durations results in significant positive effects. Since the publication of this review, similar findings emerged in studies investigating children. While some studies that utilised exercise of shorter durations (10-20 min), have observed enhancements to attention [6, 20] and executive function [9, 14, 18, 19, 21, 26, 41], many have failed to find effects on both attention [6, 15] and executive function [10, 15, 25] and one study only observed effects to executive function in children with low baseline cognitive function [8]. Moreover, no effects to working memory have been observed following exercise < 30 min in duration [9, 10, 15, 18, 19]. This is in contrast to studies that explored exercise of longer durations (> 20 min for attention and executive function, >30 min for working memory), which have consistently found enhancements to all three of these domains [6, 7, 12, 13, 24].

Moreover, the research demonstrates that the effect of duration may be domain specific, with improvements to some domains appearing from 10 min of exercise and others only appearing following longer durations of exercise. Specifically, as aforementioned, enhancements to attention and executive function [26] have been observed following 10 min of exercise whereas effects to working memory have only been observed following exercise ≥ 30 min in duration [7, 16, 23].

Overall, tentative conclusions can be made that longer duration (> 20 min) exercise may be more beneficial than shorter durations in children, as it elicits more consistent improvements across cognitive domains. Nevertheless, the fact that improvements to some cognitive domains may be gained from 10 min of exercise is positive, as this duration of activity can more easily be implemented both in school and at home. Given that there is limited research that has specifically targeted and manipulated exercise duration when investigating the exercise-cognition relationship, this is a potential avenue for future research.

More recently, there has been an increased research focus on the effects of cognitively engaging exercise, including coordinative exercise and team games, on cognition, with inconclusive results. Some evidence suggests that cognitively engaging, compared to non-cognitively engaging, exercise elicits greater improvements in attention [24], executive function [16-18] and working memory [17, 23], while other research suggests the opposite [12, 13]. This may be because there is an optimum level of cognitive engagement to elicit benefits to subsequent cognition, and thus if exercise is too cognitive challenging, particularly in young children, it may have a deleterious effect on cognition [10].

From a slightly different perspective, several studies have utilised classroom-based exercise when exploring effects on cognition [10, 15, 24, 26]. In brief, classroom-based exercise sessions are bouts of physical activity integrated within school lessons, typically relating to the academic content of that lesson 9]. Similarly, discrepancies exist within the findings in this area. It is possible, however, that the exercise duration is a significant moderator again here. Classroom-based exercise of shorter durations (≤ 20 mins) has failed to affect cognition [10, 15], but longer duration exercise (≥ 40 mins) has been shown to elicit beneficial effects [6, 24].

In addition to considering exercise duration, evidence also suggests that different intensities of exercise may affect cognition differently, with the effects again appearing domain specific. A number of studies demonstrate that moderate intensity exercise has a beneficial effect on executive function [7-9, 14, 21, 41], and there is some evidence that it may also enhance attention [6], perception [11], and working memory [7]. Additionally, research demonstrates that both moderate-to-vigorous and vigorous intensity exercise enhances attention [12, 13, 22] and executive function [17-19, 26]. However, the findings on working memory are contradictory; of the five studies that have examined moderate-to-vigorous and vigorous intensity exercise, one found positive effects to working memory [17], while four found no effects [10, 15, 19, 20]. Notably, the studies that did not find an effect on working memory utilised exercise of shorter durations. Therefore, further research is needed in order to explore the influence of exercise duration in this relationship.

Moreover, only one study has compared the effects of different intensities of exercise on cognition; the findings of this study revealed that attention improved to the greatest extent following moderate intensity compared to high intensity exercise [20]. Tentative conclusions can be drawn that moderate intensity exercise is the most beneficial for subsequent cognition in children, although future research should aim to directly compare exercise of different intensities in the same study (whilst holding other moderators such as duration and modality constant).

It is also important to note that there is some evidence that the specific nature of the exercise (e.g. intermittent vs. continuous) may moderate the effect on cognition. Lambrick, Stoner, Grigg, and Faulkner [21] compared the effects of moderate intensity continuous exercise with moderate intensity intermittent exercise on executive function. Although enhancements were observed following both conditions, intermittent exercise was found to elicit the greatest benefit. This initial evidence suggests that the nature of the exercise may influence the effects to subsequent cognitive function to a greater extent than the exercise intensity. Additional research is necessary, however, to determine the reliability of these findings and to examine whether similar findings are observed with other intensities of exercise (e.g. continuous high intensity exercise vs. intermittent high intensity exercise). Moreover, research should explore the effects of this important exercise characteristic on other domains of cognitive function. These findings are nonetheless encouraging given that the activity patterns of children are typically intermittent in nature [42] and thus such exercise models do have potential ecological validity.

3.2 Adolescents

It is also clear that exercise characteristics (intensity, duration and modality) influence the subsequent effects on cognition in adolescents, with 13 of the 15 available studies providing a favourable effect of exercise on cognition (Table 2). The most common exercise modality amongst research in adolescents was running [28, 30-32, 34, 35]. Cycling [27, 36, 39], resistance [27, 35-37, 39, 40] and cognitively engaging exercise [29, 33, 37, 40] were also popular modalities. Overall, the available evidence suggests that the exercise-cognition benefits are not exclusive to a single modality. Running appears to be the most effective modality but this is likely due to a greater emphasis of this modality within the literature. Cognitively engaging exercise, such as coordinative or games-based activities, are receiving increasing attention. The implementation of a cognitive/socially engaging element to a physical task has the possibility to confer additional benefits to cognition. Within the literature, this modality has mainly resulted in cognitive improvements [29, 33, 37] with only one study failing to provide evidence of a benefit [40]. Whilst sustained aerobic activities are the most popular, it should be noted that the intensity and duration of the activity would also partly determine how effective a particular modality would ultimately be towards cognitive function.

Indeed, it is difficult to isolate components of the exercise dose and therefore these elements should be considered in tandem. Most of the literature included focuses on moderate and high intensity exercise (see Table 2). A common method for reporting exercise intensity was in the form of average heart rate achieved during the exercise period [29, 31-33, 37]. Another common method was relative to maximum heart rate [30, 35, 36, 38-40]. Whilst the method of reporting for intensity differs across studies, there are nine classified as using high intensity, seven using moderate intensity and one using light intensity exercise in this review. Overall, both high- and moderate-intensity exercise provide beneficial stimuli for cognitive function in adolescents. Van den Berg et al. [40] failed to show an improvement in cognitive function following moderate-intensity aerobic, co-coordinative or strength exercise. One reason for this might be due to the brief period [10 min] that participants had exercised.

Exercise intensity and duration are inversely related, so for a brief period the intensity may need to be higher to elicit a positive response, or the duration of lower intensity may need to be extended. Brief exercise periods are unanimously popular (see Table 2). Specifically, exercise bouts lasting ~10 min have been studied extensively [29-32, 37, 38, 40]. In addition, slightly longer periods lasting ~20 min have also been popular [28, 36, 39], as well as maximal exercise until exhaustion [27, 34]. There is little attention given to prolonged bouts (≥ 30 min) [33, 35]. Overall, the brief periods of exercise have proven to be beneficial for cognitive function, with only a few studies failing to provide supporting evidence for executive function [38, 39], as well as for attention and working memory [40]. It is likely that the short duration is appealing for research due to the applicability of fitting into a typical school day and thus, provides strong ecological validity. Whilst most of the research pertaining to brief exercise bouts is positive for cognitive function, the combination of intensity and modality varies across studies which makes it difficult to decipher an optimum format of exercise to aid cognitive function within a school day.

Both studies using maximal exercise protocols [27, 34] lasted from 9–20 min and were unquestionably intense in nature. Despite this, they both provided evidence for benefits on cognitive function following maximal exercise. This is likely due to the slight delay given between cessation of exercise and administering the cognitive tests, which is recommended following intense exercise [2]. Worth noting, however, is that both studies used between-subjects designs, without repeated measures. Although they were counterbalanced, there is the potential for confounding factors to affect study outcomes and a within-subjects, repeated measures approach would strengthen the evidence provided.

Given the current physical activity recommendations, it is surprising that there is little research investigating longer durations (≥ 30 min). Whilst it may be seen as impractical within this population, with limited chance for exercise of these durations in a school day, there are still opportunities during lunchtime (depending on the school's policy) and Physical Education lessons. Whether these longer durations would have any effect (either positive or negative) on cognitive function, and maybe classroom performance, is something that warrants further investigation.

4. Cognitive Domain Assessed

Whilst authors often conclude generically with regards to the effect of exercise on cognitive function, it is very important to consider the domain of cognitive function that has been measured. As mentioned earlier, cognitive function broadly comprises of six domains and this review focuses on the four most studied and most important domains for academic performance in children and adolescents; attention, perception, working memory and executive function.

4.1 Children

So far, the focus within studies examining the acute exercise-cognition relationship in children has been on executive function, with fourteen of the twenty-two extant studies measuring this component of cognition post-exercise (see Table 1). Of these studies, eleven demonstrated favourable effects, while three found no effects. Moreover, of the seven studies measuring attention, six found favourable effects and one found no effect of exercise. Only one study to date has measured perception, finding positive effects of exercise on this domain. Furthermore, of the nine studies that measured working memory, four found positive effects, while five found no effects (see Table 1).

The findings demonstrate a few things. Firstly, that acute exercise has the ability to improve attention, perception, working memory and executive function. Secondly, that the effects of exercise on cognition are cognitive-component specific, and finally, that currently there are imbalances within the literature with regard to the cognitive domain assessed. Most studies have focused on executive function and significantly fewer have measured perception and working memory post exercise. Moreover, most studies (59%) have only measured one component of cognitive function, and very few studies (14%) have measured more than two (Table 1) [7, 15, 16]. It would therefore be valuable for future research to measure each of the aforementioned components of cognition following exercise. This would provide a better understanding of these domain-specific effects, would highlight how the exercise characteristics (modality, intensity and duration) may influence these effects, and ultimately would help to determine which dose of exercise affects cognition most favourably.

4.2 Adolescents

Within the adolescent literature there were many different tests used to assess cognition, covering a range of cognitive components (see Table 2). The most popular domains investigated were executive function, attention and working memory. Executive function was assessed in 8 (57%) of the included studies, with 6 (75%) of these displaying an improvement in cognition. Attention was also assessed in a similar proportion of the literature (57%), with 4 (50%) of the studies finding an improvement in cognition. There were 6 studies from the available literature that measured working memory, with 3 (50%) of these demonstrating a favourable effect. In addition, memory was measured in one study, with a positive effect of exercise shown [34]. Overall, the aforementioned studies provide strong evidence for an effect of acute exercise on subsequent executive function. The evidence for attention and working memory, however, remains equivocal. An explanation for this may be due to the variety of tests used to assess the same domain. However, more work is required on these areas to fully elucidate whether or not acute exercise affects both sub-domains differently.

The majority (57%) of the cited studies in adolescents only employed a single cognitive test in their protocols (see Table 2). Other research utilised two [35, 38, 40] and three [31-33] cognitive tests following acute exercise. Where fewer cognitive tests are employed, it is difficult to compare the effects of the same exercise across domains. Therefore, future research should use multiple cognitive tests following an acute bout of exercise to enhance understanding in the area.

Taken together, the findings suggest that whilst acute exercise is beneficial for cognitive function globally, there are domain specific effects that need to be considered. Furthermore, this adds to the complex relationship between the dose of exercise, as discussed in the exercise characteristics section, and the cognitive benefits seen in the post-exercise period.

5. Time Course of the Effects

Due to the potential impact of the exercise-cognition relationship, and the applicability with respect to a school day, the timing of the cognitive tests relative to the cessation of exercise is an important consideration in the acute exercise-cognition relationship.

5.1 Children

Most studies in children have focused on the immediate effects to cognitive function post-exercise (see Table 1). The findings from this literature demonstrate that exercise elicits significant, immediate enhancements to attention [6, 13, 15], perception [11] and executive function [8, 9, 14, 18, 19, 41]. Of the six studies that explored the immediate effects to working memory, however, only two found positive effects [16, 17], while four failed to find effects [9, 10, 15, 19].

Currently only a small number of studies have explored whether any delayed effects of exercise on cognitive function exist, but the evidence suggests that there may be delayed improvements to attention, working memory and executive function (see Table 1). Enhancements to executive function have been observed 15, 25 and 30 min post exercise [21, 22] and enhancements to working memory have been observed 25 min and 30 min post exercise [22, 23]. Moreover, improvements to attention have been observed up to 90 and 110 min post-exercise [6, 24]. The evidence in this area is within its infancy however and there is a need for future research that examines the delayed effects of exercise at numerous time points and across various cognitive domains. This will enable a more comprehensive understanding of the time course of the benefits to each aspect of cognitive function post exercise. Furthermore, future research should also consider whether the temporal nature of the effects are dependent on the dose of exercise, as there is some initial evidence that exercise of longer durations may result in longer lasting benefits to cognitive function [12, 23, 24].

5.2 Adolescents

In adolescents, cognitive tests immediately [32, 33, 38, 40] and following a delay of 10 [28, 37] and 45 min [31-33] post-exercise, were the most popular timepoints among the literature. Cognitive function was also measured during exercise [38] but failed to provide any evidence of a beneficial effect. Unfortunately, a large proportion (50%) of the available studies failed to report specifically when the cognitive tests were completed post-exercise [27, 29, 30, 34-36, 39].

The evidence regarding the effects immediately post-exercise are equivocal, with 2 studies suggesting a benefit [32, 33] and the other 2 suggesting no change [38, 40]. There is potentially a domain specific relationship with respect to the timing, as response times during an executive function task were improved immediately post-exercise [32, 33]. However, several studies failed to specify the time between the cessation of exercise and completion of the cognitive tests.

Overall, there is evidential support for the notion that acute exercise improves cognitive function, following delays of 10 and 45 min. When assessing the benefit of a delay, the exercise intensity must be considered. As suggested previously, the delay between exercise and cognitive tests provides benefit when the exercise intensity is high [2]. Overall, there remains very little evidence on the time-course following acute exercise with respect to cognitive performance. More research should be conducted investigating the transient nature of the exercise-cognition relationship in adolescents. This knowledge could have vital implications for embedding exercise within the school day so that it aids short-term cognitive performance and subsequently long-term academic achievement, if repeated chronically, as shown in the model by Howie and Pate [43].

6. Participant Characteristics

Recently, there has been an increasing awareness within research of the influence that specific participant characteristics can have on the exercise-cognition relationship. This includes the influence of baseline physical activity, physical fitness, cognitive/academic ability and weight status (see Table 1 and Table 2). Overall, the emerging evidence suggests that each of these characteristics have the potential to be significant moderating factors, yet the specific nature of their exact effects certainly warrants further investigation.

6.1 Children

In some studies, in children, low baseline cognitive performance has been associated with the greatest improvements in cognition following exercise [8, 17]. While in other studies, improvements to cognition have only been observed in children with high baseline academic performance [19]. Moreover, greater improvements in executive function post exercise have been observed in children with higher cardiorespiratory fitness levels [19], however currently no relationship has been observed between baseline physical activity levels and attention [6]. Furthermore, when considering weight status, Vazou & Smiley-Oyen [26] reported that exercise elicited the most significant enhancements to executive function in overweight children, compared to normal weight children. Despite these initial findings, research in this area is still limited and most studies have employed a between-subject study design. Whilst such an approach may be argued as being necessary for factors such as physical fitness, training and long-term intervention studies could also examine this and provide a higher quality of evidence for the moderating effects. Furthermore, the potential for these factors to affect the exercise-cognition relationship highlights the importance of future studies to report and control [where possible] these factors, to allow us to more fully understand their effects.

6.2 Adolescents

Some of the included studies accounted for participant characteristics as potential moderators for the exercise induced changes in cognitive function in adolescents. Such characteristics included cardiorespiratory fitness [33, 36, 39], age [28] and baseline cognitive performance [30]. Whilst these potential moderators are increasingly recognised broadly in the exercise-cognition relationship [3], only the aforementioned studies provide empirical evidence for their role within the adolescent population.

Cardiorespiratory fitness is positively associated with aspects of cognition, similar to those seen following acute bouts of exercise [44]; leading to an assumption of interactive effects [3]. Of the available evidence in adolescents, cardiorespiratory fitness is seen to interact with post-exercise cognitive performance positively [33, 36] whilst also displaying no interactive effect [39]. Specifically, $\dot{V}O_{2peak}$ (predicted from the multi-stage fitness test) showed that higher fit participants showed a greater improvement in response times during the Stroop and Sternberg tasks following a 45 minute delay post-exercise [33]. Furthermore, higher fit participants (established by performance on an incremental cycling test) also had a quicker response time during a modified flanker test post-exercise [36]. Electroencephalography [EEG] measurements suggested that this effect may be driven by a greater allocation of cognitive resources necessary for the completion of the cognitive task in the lower fit participants [36], resulting in a lower cognitive performance post-exercise. Using a similar incremental test to assess cardiorespiratory fitness, Stroth et al. [39] did not provide any supporting evidence on post-exercise cognitive performance, despite using the same exercise duration, protocol, intensity and the same cognitive test. Interestingly, EEG traces suggested that higher fit participants displayed enhanced task preparation as well as efficient executive control processes. Overall, the evidence regarding the interactive effects of cardiorespiratory fitness and post-exercise cognition is ambiguous and under-represented in the adolescent population and more evidence is required to clarify this relationship; with tentative conclusions indicating that higher fit adolescents may gain greater cognitive benefits post-exercise compared to their lower fit counterparts.

Whilst the available evidence spans many ages across the stage of adolescence, only one study has directly assessed whether age within adolescence moderates the cognitive response to an acute bout of exercise [28]. Investigating participants aged 10–16 years, the authors demonstrated that there was an inverse association between post-exercise cognitive improvement and age, whereby younger participants demonstrated greater post-exercise cognitive benefits. Whilst this is an interesting finding, the potential for other moderators to confound this relationship needs to be considered. Habitual physical activity and cardiorespiratory fitness are inversely related to age throughout adolescence [45]. It is plausible that this may explain the age-related decline in cognitive improvement following exercise [28]; but as this characteristic was not considered or reported, it is difficult to conclude what mechanisms might be driving the effects.

A final participant characteristic that warrants consideration surrounding the exercise-cognition relationship, is the baseline cognitive performance of the individual. Budde et al. [30] found that there was a greater improvement in attention for those participants with a lower initial performance (on the Letter Digit Substitution test). As discussed previously [3] it is logical that those with poorest pre-test results have scope for greater improvement. Conversely, those with high pre-test performance have the least scope to improve, following exercise. Indeed, this is worth noting when assessing the post-exercise improvement in cognitive function, in order to prevent potential overestimation of the effect.

Taken together, there are participant individual characteristics that have potential to moderate the exercise-cognition relationship. These characteristics and their moderating role present a lucrative avenue of research and, at the very least, they need to be carefully controlled and reported when conducting research in this field.

7. Discussion

Overall, the findings of this review are in line with previous suggestions [2-4], that an acute bout of exercise has a small, but positive, effect on subsequent cognitive function in children and adolescents. Specifically, 21 of 22 available studies in children and 13 of 15 available studies in adolescents demonstrated a favourable effect of exercise on cognition. Novel findings from this review concern the moderating variables, as well as the exercise characteristics and cognitive domains assessed, in this relationship and the very important role that they can play in determining cognitive function following an acute bout of exercise.

In children (aged 6-11 years), the available evidence suggests that the greatest cognitive benefit is likely to arise from exercise which is of a moderate intensity and greater than 30 min in duration. This may be achieved by different exercise modalities, such as walking or running. In addition, cognitively engaging exercise also has the potential to enhance cognition, though it must be noted that if such exercise is too cognitive challenging for the children (an effect which is most likely age-dependent) then such exercise may have a negative effect. Further evidence is required to more fully understand the effects of classroom-based activities on cognition. Future research should also continue to explore the influence of intermittent vs. continuous exercise on cognition, while considering the typical activity patterns of children, along with exercise models that are ecologically valid in this population. Despite the well-documented cognitive benefits of prolonged and sustained [>30 min] moderate intensity activity, this is not an exercise model that would easily be incorporated into daily life and/or adhered to by young children.

In adolescents, the supporting evidence would suggest that exercise of any modality would be beneficial for cognitive function, if it were of moderate to high-intensity, and brief (10-30 min). However, as most of the research has utilised running protocols, it is difficult to suggest an optimum modality. In addition, cognitively-engaging exercise is receiving increased attention as a successful modality which would likely suit this population. Emerging evidence is positive, however, more research is needed to strengthen this notion. Direct comparisons of exercise duration (matched for intensity) are also lacking within the literature. It must also be noted that the optimum dose of exercise for cognitive improvements may also depend on the component of cognition being assessed, the timing of the tests relative to cessation of exercise, as well as characteristics of the individual.

The timing of the cognitive tests, relative to the cessation of exercise, seems to have an important contribution to the benefits that are typically seen. The evidence suggests that the cognitive benefits from an acute bout of exercise arise immediately (except perhaps for very high intensity, fatiguing exercise) and persist for up to ~45 min. However, the effects beyond 1 hour post-exercise are rarely studied and warrant further investigation; such evidence would provide valuable insight into the transient nature of the post-exercise benefits to cognition. As it is a vital component for deciphering the exercise-cognition relationship, authors should be fully transparent about when the cognitive tests occur as this would help when synthesising the results of multiple studies.

In terms of the moderators reviewed in the acute exercise-cognition relationship, the strongest evidence currently exists for an effect of physical fitness; whereby children and adolescents with higher fitness levels gain greater post-exercise cognitive benefits compared to their lower fit counterparts. However, where higher and lower fit young people have completed the same exercise there is the potential for the exercise characteristics (the fact that the lower fit children will be working at a higher relative exercise intensity) to influence these effects. The interactions in this somewhat complex relationship certainly require further clarification.

Overall, there are a number of important recommendations for future research that is conducted in this area. These include:

- It is absolutely imperative that future studies carefully consider the factors affecting the acute exercise-cognition relationship that have been identified within this review. Wherever possible these should be controlled for, or at the very least measured and reported. This will make interpretation and synthesis of the emerging literature in this area much more informative and will allow a greater understanding of the acute exercise-cognition relationship to be developed.
- Carefully selecting the control/comparison condition in studies. A number of studies have utilised a resting control condition (sometimes this takes the form of 'normal classroom activities') whereas others have compared different forms of exercise. One important consideration is the 'cognitive engagement' of the comparison condition, with this potentially affecting subsequent cognitive outcomes. We would recommend the use of a resting (physically and cognitively, as far as possible) control condition, to truly elucidate the effects of the exercise. Future studies could also compare different forms of exercise in the same study, although should still include a resting control condition for comparison.
- Including a battery of cognitive function tests to enable the acute exercise-cognition relationship to be examined across the multiple domains of cognition. The literature reviewed here suggests that some of the effects are domain-specific and measuring across multiple domains in future studies will allow these effects to be clarified.
- Wherever possible, adopting a within-subjects design. A number of studies in this area have used between subjects designs and such designs introduce the potential for confounding variables, such as the moderators identified in Figure 1 (physical activity, physical fitness, baseline cognitive ability and weight status), to influence study outcomes. This is particularly pertinent when trying to examine the effect of the exercise characteristics as moderators on the acute exercise-cognition relationship.

8. Conclusions

Overall, the evidence reviewed here suggests that moderate intensity of ~ 30 min duration has positive effects across cognitive domains in children, whilst moderate-high intensity exercise of 10-30 min duration appears most beneficial in adolescents. Findings also suggest that the beneficial effects last for ~ 45 min post-exercise and, tentatively, may be more pronounced in children and adolescents with higher physical fitness levels. Future research in this area should carefully consider these moderating variables and continue to explore their effects. Where possible these factors should be controlled and at the very least measured and reported, to allow interpretation of the findings with respect of these very important moderators in the acute exercise-cognition relationship

Author Contributions

Ryan Williams and Lorna Hatch drafted the manuscript. Simon Cooper edited the manuscript. All authors read and approved the final version of the manuscript.

Competing Interests

The authors declare that no competing interests exist.

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